Early differentiation of the Moon from combined high precision HFSE measurements and partitioning experiments

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Introduction: The Moon provides the most accessible source of insight to the processes involved during planetary formation and differentiation. Lunar rocks represent a suite of samples that provide a snapshot of an early-formed body in the Solar System. Understanding the crystallization of the Lunar Magma Ocean (LMO) is best achieved via the combination of experimental data with natural samples. We pursue this by exploring elemental behavior, in this case where W and U are regarded as homovalent elements during partial melting in the Earth's upper mantle. However, mineral/melt experimental partitioning data have shown that U and W are less incompatible at more reduced fO_2 conditions, such as the ones prevalent during lunar mantle melting [1,2]. The higher mineral/melt partition coefficient of W^{4+} relative to W^{6+} will significantly affect the overall compatibility of W in lunar mantle residual phases during partial melting and fractionate it from U and the High Field Strength Elements (HFSE). Therefore, we combine whole-rock high-precision HFSE and Hf-Nd isotope data in lunar samples with crystallization and aggregate fractional melting models to better understand the petrogenesis of major lunar rock types and quantify the lunar W budget with implications for the ^{182}W systematics of the Earth and the Moon.

Methods: A diverse range of lunar samples were obtained from the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM), including 7 high-Ti mare basalts and soils, 14 low-Ti mare basalts, 2 ferroan anorthosites (FANs), and 7 KREEP-rich samples. Samples were documented, ground, mixed isotope tracers added before digestion, and the elements of interest were isolated for analysis on the University of Cologne's MC-ICP-MS. Residual lunar mantle mineral assemblages for our melting models used hybrid cumulate sources formed during mantle overturn, combining partition coefficients based on previous works [1,2] and additional Hf-Nd isotopic source constraints [3].

Results and Discussion: Our data for low-Ti mare basalts fall within loose ranges (U/W between 1.6 to 2.6, Hf/W between 30 to 50). Within individual groups the low-Ti basalts are fairly uniform (U/W generally varies by 0.1, Hf/W by ca. 5). Amongst the high-Ti mare basalts, the Apollo 17 samples show variable Hf/W up to 150 and correlated U/W up to 2.3, clearly distinct from the A11 high-Ti basalts (Hf/W of 40 to 60 and U/W between 1.5 and 2.2) and all low-Ti basalts. Similarly, most samples show Zr/Nb between 14 and 18 while A17 high-Ti mare basalts fall below 10. Melting models (continuous & fractional melting, ± residual metal) and the within-group homogeneity of low-Ti mare basalts imply that the source compositions per group are virtually identical but differ from group to group. This agrees with the distinct Hf-Nd isotopic and extended HFSE features found amongst different groups of low-Ti mare basalts, which require similarly distinct mantle sources [3,4]. A unique A17 high-Ti mantle source implied by Hf-Nd isotopes [3] is compatible with variable Hf/W and correlated U/W of A17 basalts given the likely presence of residual Fe-Ti oxides and metal at the source [1,2].

The ^{182}Hf-^{182}W decay system, widely used to study planetary differentiation [7], relies on the precise determination of the Hf/W ratio of planetary silicate mantles. The assumption that W was less incompatible than Hf during the formation of LMO cumulates, which became the source of lunar mare basalts [1,2,3], implicates a re-evaluation of the Hf/W of the lunar mantle. Based on our LMO crystallization and cumulate melting model, assuming that the Hf/W of low-Ti mare basalts constrain the Hf/W of the bulk silicate Moon, we can assume a Hf/W which is at the most conservative estimate 15% above that of the Bulk Silicate Earth. The ^{182}W difference between the Moon and the Earth [5,6] thus likely reflects radiogenic ^{182}W ingrowth at a distinctly different Hf/W ratio, which constrains the formation of both bodies to the first 60 Myr of the solar system, leaving only minor importance to late accretion.

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